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THE PAST, PRESENT, AND FUTURE OF *NOTHOLITHOCARPUS DENSIFLORUS* (TANOAK) AS A FOREST PRODUCTS RESOURCE

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ABSTRACT

Notholithocarpus densiflorus (Hook. & Arn.) Manos, Cannon, & S. H. Oh (Fagaceae), common name tanoak, has a reputation as a "difficult to work with" hardwood species that has been viewed at different times in history as everything from a valuable resource for edible acorns to an annoying "weed" tree that interferes with commercial forest management. This paper explores the complex character of the species from a wood products point of view and discusses the possibility of developing it as a valuable forest-products resource.

A comprehensive review of the forest-product literature reveals the many ways tanoak has been utilized. These uses have included fuel wood, lumber, railroad ties, flooring, and furniture, and as a source for leather- tanning chemicals. Early studies of the physical and mechanical properties of the wood show a similarity to many commercial hardwood species. However, tanoak has never gained the status of a preferred timber tree for forest products. This paper compiles what is known about the wood properties of tanoak and provides recommendations for successful lumber manufacturing. The risks and benefits of utilizing a species that is a known host for *Phytophthora ramorum* Werres, De Cock & Man in't Veld, the pathogen that causes sudden oak death, are also discussed from a forest-management point of view. As interest grows in developing local resources that require little transportation from source to end use, more opportunities for utilizing tanoak will likely emerge.

Key Words: California hardwoods, *Notholithocarpus densiflorus*, tanoak, wood drying, wood properties, wood utilization.

Notholithocarpus densiflorus (Hook. & Arn.) Manos, Cannon, & S. H. Oh (Fagaceae), common name tanoak, is a prevalent hardwood species in Oregon and California. It is an abundant tree in the Northern California forest, making up about 18% of the hardwood tree volume and 6% of the total tree volume in the state (Christensen et al. 2008). The species has a long history of use and abuse, and has suffered a bit of an identity crisis. Having features in common with both oaks (acorns) and chestnuts (flowers), it has had common names that have included one, the other, or both names, such as evergreen chestnut oak, California chestnut oak, tan bark oak, and tanoak. It is neither a chestnut nor an oak but has been classified in the genera *Pasania*, *Quercus,* and for most of the 20th and the first decade of the 21st century in the genus *Lithocarpus*. Tanoak is the only species of *Lithocarpus* native to North America; the other nearly 600 species of *Lithocarpus* are native to East and Southeast Asia (Govaerts and Frodin 1998). Recently, tanoak was classified in its own genus, *Notholithocarpus*—false *Lithocarpus* (Manos et al. 2008; Tucker 2012).

Over the years tanoak has been considered by many to be a unique and valuable tree species and by others a weed that should be eradicated. It was described by a well-known botanist in 1895 as "one of the most interesting inhabitants of the forests of the U.S." (Sargent 1895), and a U.S. Forest Service forest-products researcher (Betts 1911) commented in 1911 that "there seems no good reason why tanbark oak [tanoak] should not provide for all the purposes for which eastern hardwoods are imported [from the eastern U.S. to the western U.S.]." More recently, a U.S. Forest Service research scientist (Bolsinger 1988) described tanoak as "aggressively tak[ing] control of sites after conifers have been removed in logging operations. … [It is] considered a weed tree by timberland managers." It is common for commercial timberland managers in California to resort to the use of herbicides to help control the vigorous sprouting and growth of tanoak (Tappeiner et al. 1987; Bowcutt 2011). Management techniques for controlling tanoak or managing for its wildlife, watershed, or forest-product value are beyond the scope of this paper, but good introductions to this topic can be found in

McDonald and Huber (1995) and Jensen et al. (1995).

Although the commercial value of tanoak as a resource for forest products has received mixed reviews, its high value to wildlife, forest diversity, and as a food source for Native Americans has long been understood (Stuart and Sawyer 2001). Historic uses of tanoak wood and bark have included fuel wood, a source of tannin for processing animal hides, and sporadically as construction lumber and flooring. Also, the Native Americans in California recognized early on that by grinding and leaching the tannins out of the acorns, a nutrient-rich food, high in complex carbohydrates (55–69%) was obtained. It is reported that the Hoopa of Northern California preferred tanoak acorns over the true oak acorns also available to them, and that one tanoak could annually provide about one pound of food supplement per day (Jackins 2004).

Tanoak was an important resource for the leather-tanning industry in California from the mid-19th to mid-20th centuries—this is actually the source of the tree's common name. Tannin is a natural chemical found in many plants that is used to tan animal hides. Willis Linn Jepson (1911) reported that the bark of the tanoak tree has a very high concentration—about 10–29% by weight—of a high-quality tannin preferred by the premium leather industry. Jepson also reported that at peak production in the early 1900s, about 30,000 tons of bark from 120,000 trees was harvested per year to supply about 100 tanneries—leaving behind about three million cubic feet of wood, which was left to decay in the forest as only the bark was used. At that rate of consumption the industry was considered sustainable, but with continued growth the decimation of the tanoaks near the tanneries would have left a marked impression on the diversity of the forest, not to mention the "stupendous annual waste of wood" (Jepson 1911). The tanning industry started using synthetic tannins in the early 1960s, leading to the eventual end of the tanoak-bark harvest.

From the mid-1900s forward, many researchers recognized the destructive, hazardous, wasteful, and unsustainable practice of peeling bark for the tannin industry and leaving good wood to decay in the forest. In addition to the tanoak's well-known value as firewood, products from heavy timbers to flooring, fine furniture, and even pulp for making paper were tested—resulting in adequate, if not superior performance. Yet none of these products has ever generated much interest in the industrial and manufacturing marketplace. Conservative estimates reveal that about one quarter of the 3.6 billion cubic feet of tanoak in the California forests—about 6% of total hardwood and softwood forest tree volume—is of saw-log size and quality (Bolsinger 1988; Christensen et al. 2008). Harvesting only 1% of this volume would produce about 15 million cubic feet of sawn lumber for a California hardwood lumber market that is estimated to be about 150 million cubic feet in total (Shelly 1996; Laaksonen-Craig et al. 2003). A harvest of 15 million cubic feet is about 20% of the estimated annual growth of tanoak (Bolsinger 1988). This rudimentary analysis suggests that a sustainable harvest of tanoak could be a viable component of the California forest products industry (Shelly 2001).

An added benefit of harvesting tanoak could be the development of an infrastructure to provide a value-added alternative to managing diseased tanoak trees that are infested with the sudden oak death (SOD) pathogen, *Phytophthora ramorum* Werres, De Cock & Man in't Veld. Although the full impact of SOD on the mortality of tanoak across its range is not fully understood, evidence is mounting that a widespread decline of tanoak is taking place (Cobb et al. 2012). Having a viable market for tanoak wood products could provide the incentive needed to responsibly remove diseased trees from the landscape.

Methods

The focus of this paper is to examine the wood properties and lumber quality of tanoak and to evaluate the potential to grow a tanoak forest-product industry. The argument presented is based on a comprehensive review of the literature that pertains to the known record of wood properties for tanoak. The effects that *P. ramorum* has on the wood properties and the potential to use the wood from diseased trees is summarized from a three-year project that involved monitoring the collection of about 1200 tons of woody debris from Marin and Santa Cruz counties that was heavily infested with the SOD pathogen (Shelly et al. 2005). A subset of this woody debris included 24 tanoak saw-logs from Santa Cruz Co. that were processed into kiln-dried, finished lumber, which was then evaluated for yield and quality.

Results and Discussion

Wood Properties

The scientific interest in the properties of tanoak wood is centered around three time periods. The first recorded study occurred early in the 20th century (Betts 1911) at the peak of the California leather tanning industry. Interest in the species again peaked during the middle of the 20th century when the University of California Forest Products Laboratory focused on documenting the properties of the native California hardwoods (Paul et al. 1955; Randall 1956;

Schniewind 1958, 1960), and again at the end of the 20th century when communities began developing an interest in building small companies focused on local resources (Shelly 1996; Shelly and Jackovics 2001; Shelly et al. 2005). Results of these and similar studies consistently report wood-property values that place tanoak in the category of the densest (specific gravity), strongest (bending strength, modulus of rupture or MOR), stiffest (bending stiffness, modulus of elasticity or MOE), and hardest (hardness) woods of North America. Of the 113 commercial species listed in the Wood Handbook, only 19 have a greater average density (Ross 2010). This places tanoak in the same grouping as other high-density woods such as white oak, hickory, and locust.

Table 1 presents a summary of a selection of the wood properties reported in the various tanoak studies. The results are reported in two moisture-content (MC) categories, as the properties are dependent on the moisture content of the wood when tested. The mechanical properties of wood are typically measured at green moisture contents (above 30% moisture by weight as a fraction of the oven-dry mass, the nominal fiber saturation point) or air-dry moisture contents (12% MC). It can be risky to compare the results of studies done in very different time periods because of differences in test equipment and standards. For example, the comparatively low values for mechanical properties in the green condition reported by Randall (1956) could be explained by differences in experimental methods, or it could be related to sampling trees at the lower end of the expected density range for the species. Although not directly comparable, the results of all these studies are within the realm of the expected between-tree variation, and there is value in combining the results to create a composite average that then represents a greater geographic range of the trees being sampled (Table 2). Based on these results, tanoak is of similar density; is about 10–20% greater in strength, stiffness, and hardness; and is between 30–40% greater in shrinkage than northern red oak (*Quercus rubra* L.), which is used for comparison as a benchmark commercial species commonly used in hardwood manufacturing (Ross 2010). The greater mechanical-property values are beneficial, whereas the greater shrinkage is detrimental and emphasizes the importance of proper drying of the wood, which will minimize most problems associated with such high shrinkage values.

In addition to the mostly favorable comparison of tanoak wood properties to a benchmark commercial hardwood discussed above, other studies document favorable woodworking characteristics. Studies conducted at the USDA Forest Products Laboratory in the mid-20th

Table 1. Comparison of Select Tanoak Wood Properties from Various Researchers. *Based on density measured at oven-dry mass and green volume, nr – not reported.

Property	Specified moisture content condition	Study referenced					
		Betts 1911	Randall 1956	Paul et al. 1955	Schniewind 1958, 1960	Resch 1963	Shelly et al. 2005
Specific gravity*	od mass, g. vol.	nr	0.54	0.581	0.574	0.57	0.55–0.60
MOR (lbf/in^2)	green	10,110	8,866	10,470	10,140	nr	nr
MOE ($\times 10^6$ lbf/in^2)	green	1.68	1.32	1.55	1.88	nr	nr
Side hardness (lbf)	green	nr	947	nr	nr	nr	nr
MOR (lbf/in^2)	air-dried	16,000	16,300	nr	17,400	nr	nr
MOE ($\times 10^6$ lbf/in^2)	air-dried	2.1	1.80	nr	2.26	nr	nr
Side hardness (lbf)	air-dried	nr	1,400	nr	1,450	nr	nr
Shrinkage (%)							
Radial	green to oven-dry	6	nr	4.9	6.3	5	nr
Tangential		12	nr	11.7	12.0	14	nr
Volumetric		18	nr	17.3	18.7	nr	nr

TABLE 2. SELECTED, AVERAGE WOOD PROPERTIES FOR TANOAK COMPARED TO THE STANDARD VALUES FOR NORTHERN RED OAK, A BENCHMARK COMMERCIAL SPECIES.

Property	Specified moisture content condition	Average		Difference (%)
		Across studies	Northern red oak	
Specific gravity	od mass, g. vol.	0.57	0.56	1.4
MOR (lbf/in^2)	green	9,897	8,300	19.2
MOE ($\times 10^6$ lbf/in^2)	green	1.6075	1.35	19.1
Side hardness (lbf)	green	947	1,000	-5.3
MOR (lbf/in^2)	air-dried	16,567	14,300	15.9
MOE ($\times 10^6$ lbf/in^2)	air-dried	2.0533	1.82	12.8
Side hardness (lbf)	air-dried	1,425	1,290	10.5
Shrinkage (%)				
Radial	green to oven-dry	5.6	4.0	40
Tangential		12.4	8.6	44
Volumetric		18.0	13.7	31

century determined that tanoak exhibited good machining (Davis 1947) and gluing properties (Olson 1955) that compared favorably with other commercial hardwood species. Macroscopic and microscopic studies of tanoak describe it as a close-grained, diffuse porous wood with distinctive, large rays giving the wood an appearance similar to the true oaks (Schniewind 1958). These results, which collectively referred to tanoak as having "good workability," are reinforced by much anecdotal evidence shared by woodworkers and manufacturers as summarized by Shelly and Jackovics (2001).

Appearance is an important characteristic for wood that is used for furniture, flooring, or other high-value uses where the look of the finished piece is important. Appearance is a subjective criterion that is hard to quantify. For example, the large rays found in tanoak are considered by some consumers as a characteristic that should be emphasized, whereas others dislike the non-uniform appearance of large ray patterns (Fig. 1). Tanoak is also known to be susceptible to the formation of gray-brown stains during drying (Shelly and Jackovics 2001), which can add to the non-uniform appearance of the wood. These appearance issues can be minimized by following good milling and drying practices as discussed below.

Drying Characteristics

The importance of drying lumber to a moisture content compatible with the moisture conditions of its intended end-use environment is common knowledge. It is also well known that the ability to dry wood without causing serious degradation is not only a function of the manufacturing methods

FIG. 1. Appearance characteristics of tanoak wood (left—dark discoloration often found in center of mature trees, right—profile of broad tanoak rays on a quarter-sawn surface).

TABLE 3. RECOMMENDED DRYING SCHEDULE FOR TANOAK LUMBER.

Step	Wood moisture content (%)	Target conditions for the drying environment	
		Air temperature (F)	Relative humidity (%)
1	Green–50	70	55
2	50–30	80	60
3	30–25	100	85
4	25–20	110	70
5	20–15	120	50
6	15–8	140	40
7	8	140	55

and drying technique used but is also highly species dependent. Tanoak is known as a "difficult to dry" wood species (Espenas 1953; Resch et al. 1963; Shelly 1995). Tanoak has a tendency to develop excessive cell collapse, warp, and wood discoloration (stain) if not dried properly (Shelly and Jackovics 2001). The excessive cell collapse is especially problematic in the dark-colored zone of wood often found in the center of older trees (Fig. 1). This zone is independent of the juvenile and heartwood zones of trees and thought by some to be related to biological degradation (Prestemon 1967). Tanoak also exhibits more shrinkage in each of the three ordinal directions of lumber (tangential and radial to the growth rings, and longitudinal to the axis of a tree) than northern red oak (Tables 1 and 2). Shrinkage factors of 30–40% greater than the expected shrinkage for northern red oak (Table 2) is a cause for concern that emphasizes the necessity of following manufacturing practices known to help minimize shrinkage-related problems, such as the careful selection of sawing patterns (e.g., quarter-sawn) and drying practices that improve dimensional stability (Shelly and Jackovics 2001).

A review of drying methods developed by other researchers combined with the results of a tanoak manufacturing study reported by Shelly and Jackovics (2001) led to the development of the recommended drying schedule for tanoak lumber presented in Table 3 (Shelly 2005). In these studies, it was confirmed that the control of drying conditions during the early stage of drying is the most important factor in achieving high quality, dry lumber—a practice often followed with other difficult-to-dry hardwood species such as white oak (*Quercus alba* L.). It was determined that careful air drying at temperatures below 80°F—combined with high rates of air flow to quickly remove surface water away from the wood—can reduce the number of boards with severe cell collapse from 20% of the total to 2%, and the boards with severe stain from 30% to 5%. These results, combined with experiential evidence of practitioners, led to the development of the following recommended practices for producing high-quality tanoak lumber.

1. Avoid cutting lumber from the dark-colored core of the log—excessive collapse cannot be avoided in this zone;
2. Saw to maximize the amount of quarter-sawn lumber;
3. Stack lumber to dry in uniform piles with aligned stickers and a top-load restraint of at least 150 lbs per sq ft;
4. Encourage rapid initial drying of the surface at temperatures below 80°F to minimize kiln stain;
5. Air-dry to an average moisture content of about 35% (which will take four to nine months—depending on drying conditions);
6. Kiln dry to 8% moisture content following the mild kiln schedule presented in Table 3.

Impact of Sudden Oak Death

Tanoak, being a major host for *P. ramorum*—the sudden oak death pathogen, raises special utilization concerns. First, there is concern that harvesting tanoak trees, transporting logs, and processing wood may increase pathogen spread. And second, the wood of *P. ramorum*-infested trees may be too degraded to be acceptable for most potential products. Shelly et al. (2005) studied these issues and determined that the risk of spreading the pathogen through processing was very low. They found that even though the quality of lumber produced was degraded, the majority of the deterioration was in the outer one inch of the logs and that high-quality lumber could still be produced. It was also noted that lumber cut from the deteriorated zone (where it had been attacked by wood-boring beetles and exhibited early signs of wood decay) produced wood having a distinctive appearance. This type of wood (i.e., "spalted wood") is often valued as a premium product by woodworkers.

Lumber Yield

Two important considerations in evaluating the commercial success of producing lumber from any tree species are the quantity and quality of lumber that can be manufactured following

TABLE 4. PERCENTAGE TANOAK LUMBER YIELD BY PROCESSING AND QUALITY CATEGORY. a: Dickinson and Prestemon 1965; b: Shelly and Jackovics 2001; c: Shelly et al. 2005.

Quality	Un-infected by SOD			Infected by SOD	
	Green[a]	Green[b]	Kiln-dried[b]	Green[c]	Kiln-dried[c]
High	12.9	22.5	12.1	12	10.8
Moderate	40.4	48.0	55.2	44	27.3
Low	39.7	29.5	32.7	39	55.8
Cull	6.9	0	0	6	6.1

conventional milling and drying. Two studies, conducted 36 years apart, reported such data from tanoak-processing mill studies (Dickinson and Prestemon 1965; Shelly and Jackovics 2001). It is difficult to compare results from studies conducted decades apart as they likely used different processing equipment and measurement protocols. However, the results of these two studies are similar and provide the best information available on expected lumber yields.

The yield of green (not dried) lumber reported by Dickinson and Prestemon (1965) was estimated at 65% of the log volume, whereas Shelly and Jackovics (2001) reported 55% green-lumber yield. One possible explanation for the difference is that the first study selected higher-quality logs, while the second used mill-run (ungraded) logs that undoubtedly had the higher losses typical for lower-grade logs due to the higher incidence of defect zones (not SOD related). The first study only determined the volume yield of green lumber. The second also recalculated yield after the lumber was kiln-dried, taking into account the volumetric shrinkage during drying. Lumber yield after kiln drying was reduced to 46% of the original log volume. The results of these volume yield studies are similar to, but on the low side, of the accepted hardwood industry norm of about 50–60% dry-lumber yield.

The two studies cited above also provide data on the quality of lumber expected from milling tanoak logs. In order to make it easier to compare the results of these different studies, the quality categories of high, moderate, low, and cull (unusable) were used, as shown in Table 4. These categories are roughly equivalent to the National Hardwood Lumber Association lumber grades as follows: high is FAS, moderate is No. 1 Common, low is No. 2 Common, and cull is No. 3 Common. The results are in agreement with hardwood-industry expectations of producing about two-thirds of the lumber in the upper grades (high plus moderate). However, the drop in quality associated with kiln drying was greater than expected. At most, a 10% shift from high grade to moderate grade because of kiln-drying defects would typically be expected, but Shelly and Jackovics (2001) reported a 46% drop. This excessive loss of the highest-quality lumber stresses the importance of the kiln-drying operation and of following the drying schedule (Table 3) recommended by Shelly and Jackovics (2001).

The impact of *P. ramorum* on lumber yield and quality was studied by Shelly et al. (2005) in trees that had succumbed to SOD. As seen in Table 4, lumber quality was dramatically reduced in infested logs. After kiln-drying, only 38% of the lumber remained in the upper grades. Such a reduction in quality would seriously jeopardize the economic viability of a sawmill operation working only with infested trees. A possible solution to reducing this impact is to develop a management plan that identifies diseased trees for milling before major deterioration has occurred.

Potential Uses

Tanoak has at one time or another been used successfully in a wide variety of products. These include tannin, acorn meal, fuelwood, railway ties, truck and railcar flooring, mine timbers, dunnage, flooring, furniture, and paper pulp. These continue to be viable product options for tanoak. Low-quality tanoak biomass is also used in California as a component of biomass fuel for biomass power plants. It also has the potential to become a feedstock for chemical production including transportation fuels. Higher-quality tanoak resources are perhaps best suited for value-added wood products (Fig. 2). For example, a small sawmill in Santa Cruz Co., California has, for more than a decade, been harvesting, sawing, and kiln-drying tanoak lumber to produce hardwood flooring (Fig. 3).

Summary

Tanoak is unlikely to ever be harvested in large enough quantities to displace a commodity hardwood lumber such as red oak, but many opportunities exist to create local or niche markets that emphasize its many positive attributes. A comprehensive review of tanoak studies revealed that many of its wood properties are comparable, and in some cases superior, to popular, commercial hardwood species. But these studies also identified processing concerns that need to be addressed in order to sustain an economically successful enterprise. Recent studies that focused on the drying properties of tanoak

FIG. 2. Example of products produced from tanoak lumber (left—hardwood flooring, right—hand-hewn bench).

offer recommendations that minimize drying defects and increase the chances of operating a successful business. Emphasizing the special character and unique appearance of tanoak was also discussed as a positive marketing tool.

Recent studies also confirm that lumber can be produced from *P. ramorum*–infested tanoak trees, but at a diminished value compared to healthy trees. For sawmilling to be a viable management option in areas with SOD, it is absolutely necessary to follow the best manufacturing practices and understand the inherent risks associated with tanoak, such as excessive shrinkage and the strong tendency to develop drying defects. These recommended practices include sawing logs in order to avoid any dark-colored core wood and maximize quarter-sawn lumber, stacking the lumber properly, using top-load restraint, and following the mild-drying schedule presented in Table 3.

FIG. 3. Tanoak lumber stacked and ready for loading into a low-temperature, forced-convection, lumber dry kiln at a small mill operation in Santa Cruz Co., California.

Tanoak is a resilient forest species with many attributes and one that can be effectively managed to create a sustainable utilization strategy. Harvesting tanoak trees contributes to management strategies for controlling *P. ramorum* by creating a market for infested wood, thus removing some of the pathogen load from the forest and reducing the hazards associated with dead trees, especially in the wildland/urban interface. Opportunities also exist to expand the tanoak product market by focusing on the consumer preference of buying value-added products made from local resources by local producers. These attributes are recognized as positive benefits to growing the market for tanoak products.

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